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**THE RATE OF SETTLING OF SOLID PARTICLES  
IN  
WATER-IN-OIL EMULSIONS**

**BY**

**EDWARD TIPMAN B.Sc.**

**1955**

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## ABSTRACT

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The settling rates of particles in emulsions of water in mineral oils were studied by measuring the rates of fall of five sizes of steel balls ranging from 1/16 to 1/4 inch in diameter in an apparatus which incorporated the basic design of a falling-ball viscometer. Two refined mineral oils, two kerosine-diluted McMurray oil-sand oils, the McMurray oil itself and the water emulsions of these oils were studied. The water concentration ranged from 0 to 35% by volume at temperatures from 70 to 180°F. Stokes's Law corrected for wall effects was used in comparing the predicted with the determined rates of fall. An increase in the water concentration of any emulsion reduced the rate of fall. The emulsions were found to be Newtonian in character in the temperature range studied. The viscosity of an emulsion as determined by conventional means was found to apply in the Stokes's equation for determining the terminal velocity of a particle under conditions of laminar flow. The viscosity of an emulsion of the McMurray oil in terms of the viscosity of the dry oil and the water concentration was found to be

$$\eta = \eta_0(1 + c + 14c^2 + 26c^3),$$



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THE RATE OF SETTLING OF SOLID PARTICLES  
IN WATER-IN-OIL EMULSIONS.

A DISSERTATION  
SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES  
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OF MASTER OF SCIENCE.

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DEPARTMENT OF CHEMISTRY

by

EDWARD TIPMAN, B.Sc.

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# THE RATE OF SETTLING OF SOLID PARTICLES IN WATER-IN-OIL EMULSIONS.

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## INTRODUCTION

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The handling of heavy crude oils has been made difficult by the presence of suspended solids in the oils. This is particularly true of heavy crude oils produced from sandstone reservoirs, because quite often the sandstones tend to be unconsolidated with the result that sand particles are produced with the oils. The effect appears to reach very troublesome levels with one particularly heavy oil obtained from a completely unconsolidated sandstone - the McMurray oil of Alberta. The McMurray oil sand is mined, and the oil is obtained from the reservoir rock by treatment of the mined sand in a surface separation plant. The Hot-Water Washing method as devised by Clark (7) uses hot water to wash the oil away from the sand. The separation of the sand from the oil is not entirely complete and the recovered oil may contain up to ten per cent of solid material.

Most oils produced from sandstones contain not only sand particles but appreciable quantities of water as well. Oil recovered by the hot-water separating process may contain water up to a concentration of 35% by volume. This double contamination aggravates an already difficult handling problem, because not only



does the sand tend to come out of suspension, but the water appears to affect the sand settling in an ill-defined manner. In refineries the settling of solids is of greatest concern in surge tanks where the sand tends to accumulate, thus requiring frequent clean-outs. On the other hand if action is taken to remove the suspended sand, the settling is slow and incomplete and results in a difficult pollution problem in refinery waste streams.

The present study has been directed toward obtaining a better understanding of the factors involved in the settling of sand particles in an emulsion of water in oil. Some of these factors can be enumerated as follows:

1. Size of the solid particle.
2. Temperature of the emulsion.
3. Water concentration.
4. Viscosity of the oil.
5. Size of the water droplets.

Stokes's Law appears to be a logical starting place for a detailed inspection of the various factors involved. In the following discussion the applicability of Stokes's Law to the present problem will be examined.

### Theory

Stokes's Law describes the terminal velocity of the unhindered settling of a spherical particle in a continuous viscous medium:



$$V = \frac{2r^2 g (d_1 - d_2)}{9 n}$$

where

$V$  = terminal velocity,

$r$  = radius of the particle,

$g$  = acceleration due to gravity,

$d_1$  = density of the particle,

$d_2$  = density of the viscous medium,

$n$  = viscosity of the medium.

Six conditions must be fulfilled in order that Stokes's Law shall hold. It is required that;

- (a) the motion of the sphere relative to the fluid be slow,
- (b) the fluid be infinite in extent,
- (c) the fluid must be homogeneous,
- (d) the sphere be rigid,
- (e) the motion be steady and free from accelerations,
- (f) that there be no slip between fluid and sphere,  
i.e. the fluid film in contact with the sphere  
moves with same velocity and direction.

Assumption (a) states that the motion of the sphere relative to the fluid must be slow. The Reynolds number can be used in determining whether a particle is falling in the laminar or turbulent flow region. This number can be calculated for any flow system.



$$\text{Re} = \frac{V_m D d_l}{n}$$

where

Re = Reynolds number,

$V_m$  = maximum velocity of the particle,

D = diameter of the particle,

$d_l$  = density of the liquid,

n = viscosity of the medium.

A particle is in the region of laminar flow if the Reynolds number is less than three, and in the turbulent region if the Reynolds number exceeds 300. Stokes's Law applies only in the region of laminar flow. Oseen (17) showed that the velocity predicted by the Stokes's equation agreed to one per cent of the determined value when the Reynolds number was one. Closer agreement was obtained for lower Reynolds numbers. Rayleigh (18) deduced the criterion that the velocity is small when the Reynolds number is less than one.

The failure of assumption (b) to be fulfilled gives rise to two effects:

1. The effect of the walls of the containing vessel.
2. The effect of the lower end of the containing vessel.

Much work has been done by investigators to derive a correction factor for the wall effect. First of them was Ladenburg (13) who obtained the formula



$$V_L = V_S \times \frac{1}{\left(1 + 2.4 \frac{r}{R}\right)}$$

where  $V_L$  = velocity as corrected by Ladenburg  
 $V_S$  = velocity as predicted by the Stokes's Equation  
 $r$  = radius of the particle  
 $R$  = radius of the tube.

Barr (4) derived the formula

$$V_B = \frac{V_S}{1 + 2.4 \left(\frac{r}{R}\right) + 2.4 \left(\frac{r}{R}\right)^2}$$

Munroe (15) has suggested a correction for lead shot falling in water which would lead to the correction

$$V_M = V_S \left[ 1 - \left(\frac{r}{R}\right)^{3/2} \right]$$

Lunnon (14) obtained the correction

$$V_{Lu} = V_S \left( 1 - 0.25 \frac{r}{R} \right)$$

Two of the most recent workers in this field, namely, Francis and Bacon have developed more complete wall correction factors.

Francis (10) proposed two correction factors, depending on the viscosity range of the viscous medium.

$$V_F = V_S \times \left( 1 - \frac{r}{R} \right)^{2.25}$$

for viscosities in the order of 720 poises and

$$V_F = \frac{V_S}{\left( \frac{R - 0.475r}{R - r} \right)^4}$$

for liquids of lower viscosity. e.g. 4 poises.

Bacon (2) checked the Faxen (9) formula and found it to be



$$V_B = V_S \times \left[ 1 - 2.104 \left( \frac{r}{R} \right) + 2.09 \left( \frac{r}{R} \right)^3 - 0.95 \left( \frac{r}{R} \right)^5 \right]$$

It is apparent from all the foregoing correction factors that the magnitude of the correction factor approaches one as the ratio  $\frac{r}{R}$  approaches zero. Thus the wall effect is least important with the smallest particles in the present study. It is important to note that for a given viscometer and a given particle the wall effect is apparently not affected by the viscosity of the medium, since none of the correction factors include a viscosity term.

The end effect of the viscometer was studied by Francis (10) and even under very extreme conditions he found that this effect could be considered negligible.

When a particle is dropped into a viscous medium, it accelerates, and after some distance of fall, it attains its maximum velocity. Bacon (2) found that four centimeters of free fall was the minimum safely allowable for good work, six or eight would be better.

Assumption (c) states that the fluid must be homogeneous. The present problem of the settling rates of particles in water-in-oil emulsions apparently falls outside this limitation of Stokes's Law.

Assumptions (d), (e), and (f) are fulfilled with solid spheres falling in a viscous medium. Bingham (5) has concluded that slip does not occur when the fluid wets the solid particle.



The viscosity coefficient of an emulsion in terms of the viscosity of the continuous phase and the volume of the disperse phase was given by Einstein (8) as

$$n = n_0 (1 + c)$$

where  $n$  = viscosity of the emulsion,

$n_0$  = viscosity of the continuous phase,

$c = \frac{\text{total volume of particles (or disperse phase)}}{\text{total volume of system.}}$

Einstein (8) later revised the expression to read

$$n = n_0 (1 + 2.5c)$$

Harrison (11) found the value of 4.75 for the coefficient of the concentration term to hold for starch emulsions up to a concentration of 30% of the disperse phase. Hatschek (12) suggested a coefficient of 4.5 which he found to hold for emulsions up to 40% of the disperse phase. The present accepted value is 2.5 and this equation called the Einstein equation is widely used.

It is interesting to note that particle size does enter into the above equation. The viscosity of the system is a linear function of the volume concentration of the disperse phase only.

In summary, although some study has been given to the viscosity of emulsions, the data appear to offer little in the present study. It has not been established whether or not the Stokes's predictions can be extended to non-homogeneous systems; it is not clear whether or not a measured viscosity of an emulsion has any direct significance for the rate of fall of a particle in



an emulsion.

### Scope of Present Study

A direct approach to the problem was indicated. Laboratory equipment was designed and built for the direct determination of the rate of fall characteristics of solid particles in emulsions of water in oil. Although the apparatus incorporated the basic design features of conventional falling-ball viscometers, the study was concerned directly with the rate of fall characteristics of particles in emulsions, rather than with the viscosity of the emulsions as such.

To simplify the system, spherical particles were used. A wide range of particle sizes was employed. Determinations were made on both refined oils and a heavy crude oil; determinations were made on a range of emulsions of the same oils. The rate of fall characteristics were determined over a range of temperatures.



## EXPERIMENTAL

### Apparatus

The apparatus used in the present study is illustrated in Fig. 1. A piece of brass pipe,  $\frac{1}{16}$  wall thickness and  $2\frac{3}{8}$  inches internal diameter, 5 feet  $6\frac{1}{2}$  inches long was used as the settling tube. Extreme care was exercised to get this tube in a vertical position so that any spheres dropped from the top would travel down the axis of the tube. This was done by means of a plumb bob. Co-axial to the brass tube, a piece of galvanized pipe four inches in diameter was soldered on to the brass tube, through which constant temperature water could be cycled to keep the material in the tube at the desired temperature.

Measured amounts of water from a 500-ml. burette could be added through an off-take tube fastened to the bottom of the falling-ball assembly. An inverted mercury bubbler was placed between the burette and the off-take tube to give some indication as to whether the water was being injected in a steady stream, or drop-wise. A piece of transparent Tygon tubing was placed in the line after the water injector, so that the material under study could be visually examined.

The material under study was cycled by means of a positive-displacement type gear pump driven by a  $1\frac{1}{2}$  h.p. electric motor. Cycling rate was measured by a standard type commercial flow-meter.



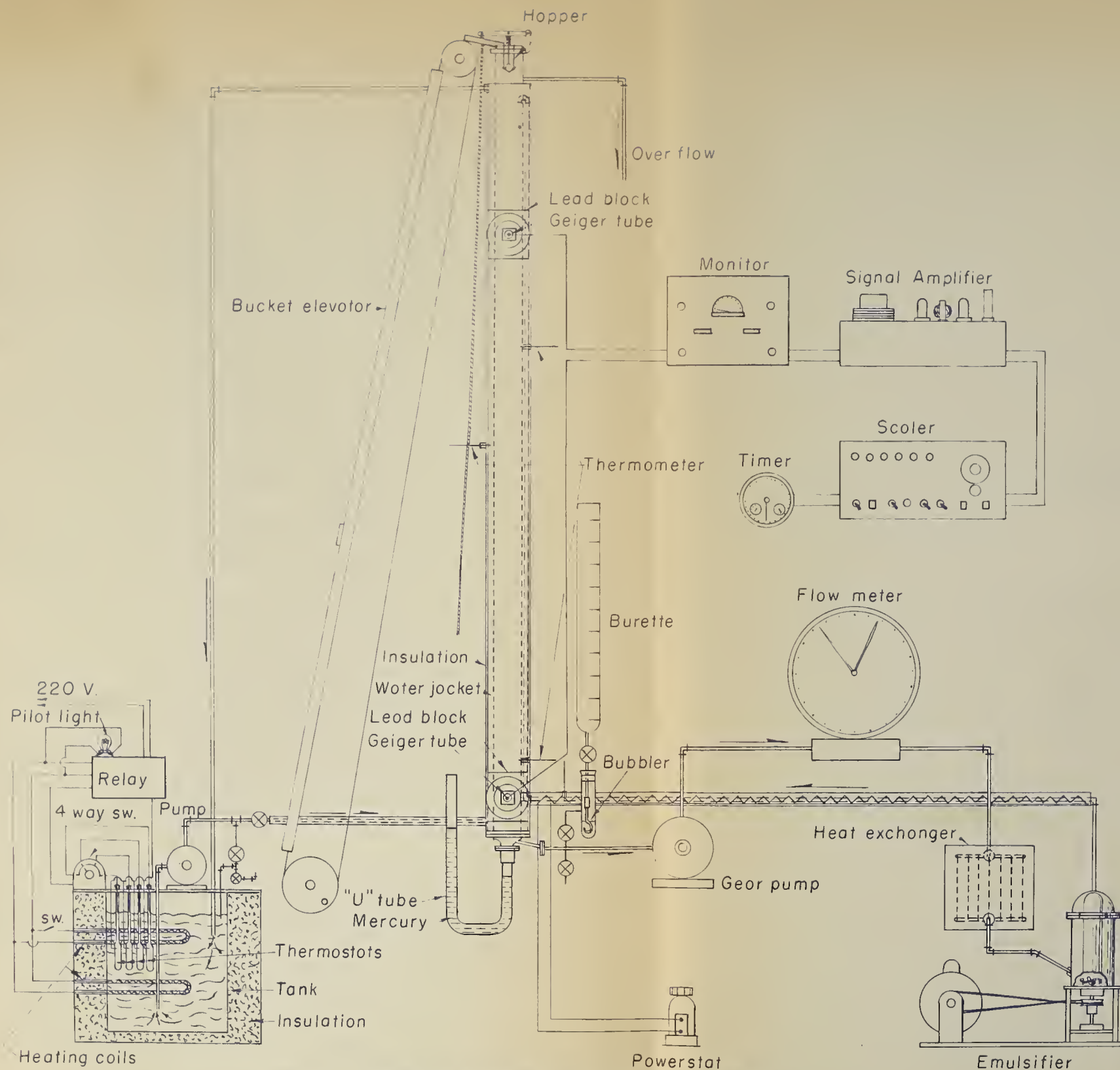


Fig. 1. Diagram of apparatus used in study of rate of fall of solid particles in water-in-oil emulsions.



To facilitate cooling the material while it was being cycled, a 7 - tube heat exchanger built in a galvanized tank was installed after the flow-meter.

To prepare the emulsion, a Waring Blender was re-designed with a metal mixing chamber. The original motor was removed and the rotor blades driven by a 1/4 h.p. motor at a speed of 5300 r.p.m.

After the emulsifier, the material passed through a copper tube around which was wrapped a 500 - watt electrical heater. This facilitated heating the emulsion when higher temperatures were desired. To facilitate keeping the emulsion at constant temperature, the return line passed into the annular space between the brass tube and jacket at the bottom of the assembly, and led to the top while immersed in constant temperature water. Copper fins were welded on to the copper return pipe to facilitate heat transfer. The return line emptied back into the brass tube about four inches below the overflow. The return discharge tube was bent into a U shape so that the emulsion discharged downward into the tube below the surface, thus preventing any swirl which might entrap air. It was considered very essential that all air be excluded from the material under study.

Since the emulsifier was at the lowest point of the system, a valve was attached to it and oil under pressure from a



small tank was forced through to fill the system.

To lift the balls to the top of the brass tube, a small bucket elevator was designed which elevated the balls and then deposited them into a small clam-shell type hopper. By pulling a string, these clam shells could be made to open, thus releasing the ball. This type of release mechanism was thought advisable since it gave no spin to the released ball. Care was exercised to be positive that the ball was released directly along the vertical axis of the tube. The ball fell through air a distance of one inch before entering the emulsion.

At the bottom of the tube the ball was recovered in the following manner. Mercury in a plastic U-tube fastened to another outlet at the bottom of the tube, confined the emulsion to the tube by means of equal hydrostatic pressure. After the ball fell through the test emulsion in the tube it came to rest at the mercury-emulsion interface. By means of a powerful permanent magnet, the ball could be dragged through the mercury to the open end of the U-tube. An organic solvent filled to a height of about two inches above the mercury at the open end of the tube cleaned the oil off the ball so it was free of oil when returned from the system.

Temperature control of the emulsion was attained by cycling constant-temperature water through the water jacket. The constant-temperature water bath had a capacity of about five gallons, and the water was pumped by means of a small centrifugal pump. Four pre-set



thermostats for temperature control at 100°, 130°, 160° and 180°F. operated a relay circuit which kept the water bath at the desired temperature. Temperature control was accurate and reproducible to  $\pm 0.2^\circ\text{F}$ . Below-room temperatures were obtained by cooling the bath manually with ice to the desired temperature.

Emulsions of water in heavy crude oils are opaque. To make possible a study of the fall characteristics of the steel ball, it was irradiated by the Atomic Energy of Canada, Ltd., Chalk River, Ontario, to produce a small concentration of radioactive isotope of iron  $\text{Fe}^{59}$   $\left[ \text{Fe}^{58} (n, \gamma) \text{Fe}^{59} \right]$  which could then be detected by suitable radiation detectors mounted outside the tube. Two end-on Geiger tubes were used to detect the gamma radiation from the ball. One was mounted 19 inches below the emulsion level, a distance great enough to permit the ball to reach its terminal velocity. The second was mounted 43.75 inches below the first, or 3 1/2 inches from the bottom of the tube. The Geiger tubes were shielded from stray radiation by a minimum of one inch of lead and were exposed to ball radiation by a window 1/4 inch x 1 inch between the tube and the viscometer.

The two Geiger tubes were connected in parallel to a Tracerlab Laboratory Monitor. The pulse signal from the monitor was fed into an electronic timing circuit. Basically, the circuit was designed to start a counter when the ball passed



the upper Geiger tube, and stop the counter when the ball passed the lower Geiger tube. The rate-meter signal was amplified about ten-fold, and the amplified pulse fired a thyratron tube to send a pulse into a subsequent circuit to start a mechanical counter counting a sixty cycle signal through a conventional scale of  $64$  scaler. The second rate-meter signal sent a corresponding pulse to stop the timing circuit.

The timing circuit illustrated in Fig. 2 had to be designed in such a manner as to measure the time for both rapidly- and slowly-falling balls. A large ball in an emulsion at a high temperature fell the distance between the two Geiger tubes in about one second, while a small ball at the lowest temperature took about 10 minutes. Since the timing device was actuated by radiation from the steel ball in front of the window, a small ball passing the window had time to start and stop the timer several times before falling out of range of the tube. Consequently to afford proper action with both large and small balls, it was necessary to design the timing circuit with a variable time constant. This was accomplished by a capacitor-resistor combination connected to the plate of the thyratron. The time required for charge to accumulate on the condenser determined the interval during which the tube would not fire no matter what signal came from the rate-meter. To allow flexibility, this time was variable by means of the choice of resistor. The time during which the tube would not fire was given approximately by the capacitor-resistor product.



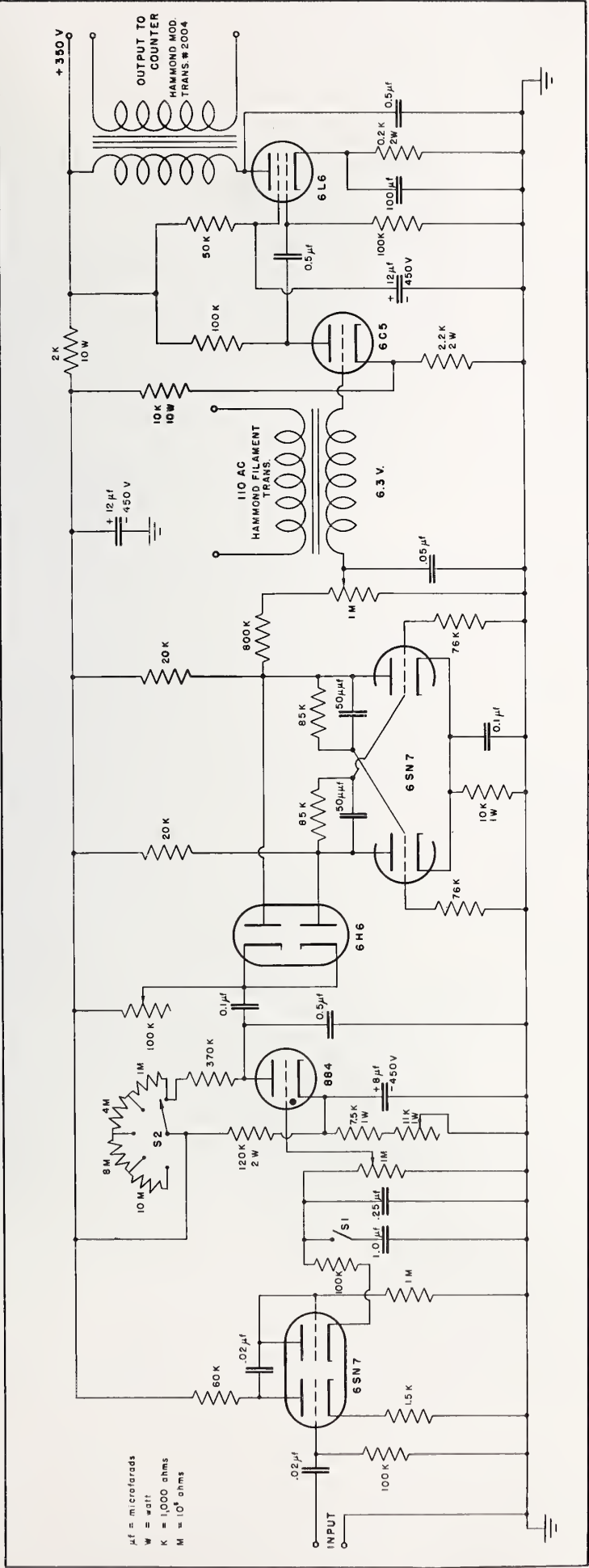


Fig. 2. Electronic switching circuit for timer.



## Materials

Crude black oils contain naturally occurring emulsifying agents. Because the role of emulsifying agents in the present study was difficult to predict, attention was directed first to moderately viscous oils free of emulsifying agents. For this part of the investigation two refined mineral oils free of detergents were used:

1. Aviation Grade 100 lubricating oil, having a viscosity of 2.160 poises at 100°F., and
2. Aviation Grade 140 lubricating oil with a viscosity of 3.896 poises at 100°F.

Following the investigation of the refined oils, the study was extended to McMurray crude oil. The oil used was obtained from a hot-water separation process in the pilot plant of the Government of Alberta at Bitumount, Alberta. In the plant process the oil was obtained as a wet crude oil, containing up to 5% solids and 35% water. This intermediate oil product was cut back with a 30° A.P.I. diluent to the extent of about 30% and then settled to remove the major part of the solids and about one third of the water. The wet diluted oil was then flash distilled to remove the remaining water. The dry diluted oil was freed of its diluent by another flash distillation. The final plant product was only slightly different from the native oil, having lost about four per cent of



its bulk as light ends in the flash distillations. The inspection of the oil is shown in Table I.

Table I  
Inspection of McMurray Oil

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| Distillation Range *, °F.:                           |     |       |
|------------------------------------------------------|-----|-------|
| Initial Boiling Point                                |     | 206   |
| 5% recovered at                                      |     | 329   |
| 10%                                                  | " " | 383   |
| 15%                                                  | " " | 431   |
| 20%                                                  | " " | 475   |
| 24.5%                                                | " " | 506   |
| Evidence of cracking at highest temperature reached. |     |       |
| Specific Gravity, 60/60°F.                           |     | 1.031 |
| Viscosity **,poises at 100°F.                        |     | 72.84 |

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\*United States Bureau of Mines Vacuum Distillation at 40 mm.

\*\*According to Ward and Clark (19) the viscosity of McMurray oil varies from 100 to 5,000 poises at 100°C depending on the particular area of the McMurray deposit the oil originated.

The McMurray oil contained 1.92% solids. Analysis of the solids by X-ray diffraction showed the presence of kaolinite, pyrite, illite, and quartz. The first three were classed as major



components, i.e. the concentrations were greater than 20% of the total. Quartz was present in moderate amounts -- about 15-20%. One component present in minor amounts -- about 5% could not be identified. Particle size of the pyrite and quartz was less than 10 microns, and the major part of the solids was minus 200 mesh.

The McMurray oil was very viscous and fell outside the range of viscosities attainable with the refined oils. Consequently a series of black oils with varying viscosities was prepared by diluting the raw oil with kerosine so that direct comparison with the refined oils would be more nearly possible. The series of black oils consisted of:

1. McMurray crude oil,
2. McMurray crude oil blended with 6.28% (vol.) kerosine,
3. McMurray crude oil blended with 16.9% (vol.) kerosine.

Six sizes of commercial steel ball-bearings in sizes of 1/16, 3/32, 1/8, 3/16, 1/4 and 3/8 inches diameter respectively, were used. The balls were checked for size and sphericity with a micrometer and found to be accurate to 1/10,000 of an inch. A number of the same size of balls was weighed and all checked in weight to a tenth of a milligram. The steel balls were considered therefore to be uniform and accurate enough for this investigation.

To correct for the change in density of the steel balls at the various operating temperature, the coefficient of cubical



expansion for iron i.e.  $0.3350 \times 10^{-4} / ^\circ\text{C}$  was used.

A minimum activation of 5 micro-curies per ball was found to be the minimum energy level to operate the timing device. The Fe 59 isotope is characterized by gamma radiations of 1.30 and 1.10 m.e.v. energy and a half life period of 46 days. It was customary to irradiate the balls to a minimum activity of 20 micro-curies per ball in order to assure a convenient experimental period without introducing severe health hazards.

The balls at all times were handled with tongs. Cleaning the balls after they were taken out of the apparatus was done by rubbing them between a cloth pad and a cloth covered brush with a 1/2 inch lead top. When not in use, the balls were kept in a lead castle with 1 1/2 inch lead walls.

Distilled water was used for making the emulsions. Emulsions containing approximately  $2\frac{1}{2}$ , 5, 10 20 and 30% water were used for the study.

#### Analytical Procedures

Water content for all samples was done by A.S.T.M.\* procedure D95-46 for water in petroleum products and other bituminous materials. In this procedure, a measured quantity of sample was mixed with 100 ml. of toluene and placed in a 500-ml. boiling flask connected to a trap and condensor. Heat was applied, and the water

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\*American Society for Testing Materials



and toluene were driven off, condensed and collected in the trap. The toluene being of lower specific gravity than the water, overflowed and returned into the boiling flask. The volume of the water was determined from calibrations on the trap and the percentage water in the sample calculated.

The percentage of kerosine added to the McMurray oil was determined by A.S.T.M. Procedure D 322-35 for dilution of crankcase oils. A measured quantity of sample was placed with approximately 500 ml. of water into a litre boiling flask, connected to a special trap and reflux condensor. Boiling the mixture gave a vapour of steam and kerosine which was condensed into the trap. An off-take from the bottom of the trap allowed the water to flow back into the flask, leaving the kerosine in the trap where it could be measured.

Solids in the McMurray oil were determined by A.S.T.M. procedure D 473-48 for sediment in fuel oil by extraction. Ten grams of sample accurately weighed were placed in a special weighed porous alundum thimble. Benzene was refluxed through the thimble until all the oil was washed from the sediment. The thimble was again weighed and the percentage solids calculated.

Viscosity was determined by A.S.T.M. procedure D 445-52T for test of kinematic viscosity. This test uses Modified Ostwald viscosity tubes. The time for a measured amount of liquid to



flow through a capillary was determined. The product of the time and the tube constant gave the viscosity in centistokes. Multiplying this viscosity by the density gave the viscosity in centipoises.

The present accepted standard for viscosity determination, accepted July 1, 1953 by A.S.T.M. is 1.0038 centistokes for water at 68°F. This new value has been used for all viscosity determinations in this investigation.

Density measurements were done by A.S.T.M. Procedure D 287-52 for density of petroleum and its products by hydrometer.

#### Experimental Procedure

The falling ball assembly was filled with oil by attaching a copper tube from a five-gallon oil tank to the valve at the bottom of the emulsifier chamber. This point of oil injection was chosen because it was the lowest point in the system, and by sweeping out the air in front of the oil, air entrainment would be minimized. The tank from which the oil was drawn was pressurized to about 10 p.s.i. The oil injection was continued until oil came out of the overflow.

After filling, the oil was allowed to stand for a period of about thirty minutes in order to allow any air which may have become entrapped in the oil to float to the surface. Then approximately one half-gallon of oil was cycled with the pump and the oil



left again for a half hour period. One-half gallon represented approximately the volume of oil held by the pump-motor-emulsifier section of the apparatus. This cycling procedure was then repeated.

In order to further check for the presence of any air in the oil, the oil was cycled and the stream examined visually by placing a light behind the Tygon viewing tube. No air bubbles were ever observed in the two aviation lubricating oils. By using the same filling technique with the black McMurray oils, which could not be inspected visually, it was reasonably certain that the oils were free of air.

When a heavy McMurray oil was to be studied in the apparatus, the oil was first heated on a steam radiator while in the tank, tightly covered. The circulating water was heated to about 150°F. and the warm oil then injected.

To prepare an emulsion for study, water under pressure from the burette was injected into the oil stream. By watching the action of the mercury surface in the bubbler, it could be observed whether the water was entering dropwise or in a steady stream. The drop-rate was adjusted according to the volume of water which was to be added, a low rate for emulsions of low water concentration. For the lower water concentrations, the addition was adjusted so that approximately 20 complete cycles of the oil were made during the injection. For higher concentrations, approximately 30 complete cycles were made. During the water addition



the emulsifier was operated at full speed. After the desired amount of water was added, the cycling was continued for another six cycles in order to smooth out any minor variations in water content.

During the preparation of the emulsion, the temperature rose due to the heat generated by the pump and emulsifier. Packing of the heat exchanger with ice was insufficient to absorb this heat. For operation at 70°F. the constant temperature water bath was cooled with ice added manually. Since after the preparation of the emulsion, the temperature was approximately 85°F. the water had to be cycled around the tube until the temperature dropped to 70°F. After cooling to 70°F. water was cycled through the jacket for half an hour to allow the emulsion to come to a uniform temperature.

For operation at 100, 130, 160 and 180°F., the emulsion was cycled with the emulsifier in operation until the desired temperature was reached. With a Variac control, the heat input of the electrical heater around the return line was adjusted so the bath and emulsion temperatures rose together. Since the emulsion was heated while being cycled, when cycling was stopped the temperature was considered to be uniform throughout the emulsion. However, the emulsion was allowed to stand for a ten-minute period to even out any variations in temperature.



To determine settling rates, a steel ball was elevated to the hopper at the top of the tube, and by pulling the trip cord, released. The time interval between the passages of the ball past the top Geiger tube and past the lower tube was recorded by the scaler. The large balls were dropped first. A minimum of five drops for each ball was taken and the fall times averaged. Indication of reproducibility of timing of five successive runs on a particular ball gave readings of 6.83, 6.97, 6.90, 6.77 and 6.87 seconds respectively.

Because the Geiger tubes were sensitive to stray radiations due to the balls being in the same room even though they were stored in a thick lead castle, and cosmic rays which were always present, the gain setting on the electronic circuit had to be such that the circuit would not fire on base count. This became important when the balls were approaching the end of their useful radio-active life. Sometimes when a slow-moving ball which was low in radioactivity was approaching the position when it would fire the tube, a burst of stray rays would pass through the tube causing the timer to start. The monitor was equipped with a speaker so this could be audibly detected. Readings which were thus obtained were considered unreliable and discarded. After some experience with the apparatus it was possible to differentiate between the burst of radiation which were caused by stray rays and those which were given by the steel balls.

After a particular ball was passed through the emulsion, it was recovered by dragging it through the mercury in the U-tube with



an external magnet.

It was possible to make a complete run on one oil or emulsion at the five different temperatures in one day. After a day's run, the emulsion was cycled and samples were drawn off from a valve located at a point close to the bottom off-take of the tube.

Once the study of a particular oil was started, the copper tube connecting the tank and the apparatus was left connected. This was done to prevent the possibility of any air being put into the system while re-filling. Before the start of the next run at a higher water concentration, material in the apparatus was replenished with fresh oil.

Between runs using different oils, the apparatus was completely flushed out by using several fills of either kerosine or diesel fuel. It was then filled about half full of the next oil, cycled and drained. This process was repeated. The third time, the apparatus was completely filled with oil, cycled and drained. With this procedure on aviation oils, all traces of water were removed from the apparatus. The same method was used for the McMurray oils.

To test the stability of the emulsions used in the study an emulsion of approximately 20% water in Grade 140 aviation oil was prepared. A sample of the emulsion was withdrawn from the



apparatus and photographed immediately. Successive photographs were made of the same emulsion over a period of one week with the emulsion at room temperature. All photographs taken over this period are shown in Plate I. No distinct separation could be observed in the emulsion until a period of four days had elapsed. As a result it was concluded that the emulsions were stable during the time required to drop one series of balls, approximately one hour.

The emulsions of the McMurray oils appeared to be more stable than the one prepared from the aviation oil. These emulsions showed no indication of breaking over a six month period.

To determine particle size of the disperse phase an emulsion of 18.7% water in Grade 140 aviation oil was prepared, a sample withdrawn and a photomicrograph taken. The picture obtained is shown in Plate II and indicates the range of water droplet diameter was from one to twenty microns. Since the McMurray oils were extremely opaque, it was difficult to obtain a microphotograph of one of the emulsions. However, it was considered reasonable to assume that the particle size of the disperse phase was approximately the same in both the aviation and McMurray oils.





0



5 MIN.



20 MIN.



1 HR.



5 HRS.



1 DAY



4 DAYS



1 WEEK

Plate I. Photographs illustrating stability of emulsions of 20% water in Grade 140 aviation lubricating oil at room temperature.



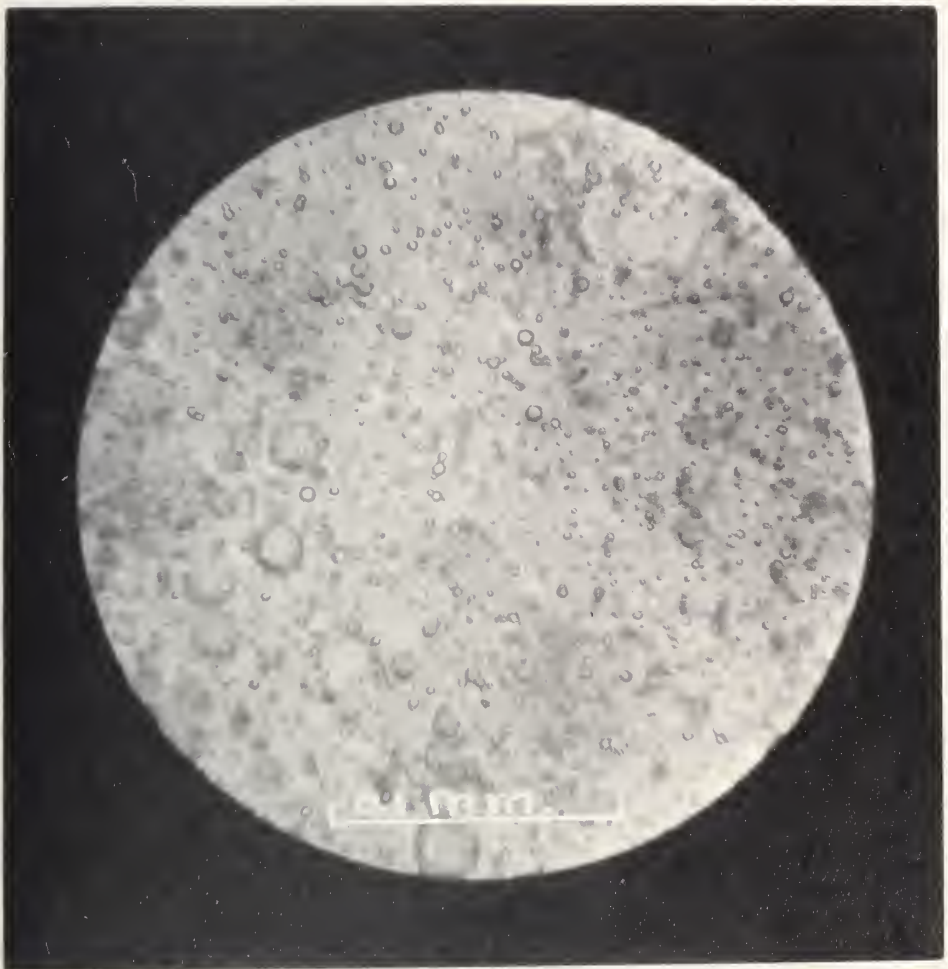


Plate II. Photomicrograph illustrating particle size of water droplets in emulsion of 18.7% water in Grade 140 Aviation lubricating oil.



## RESULTS AND DISCUSSION

The rates of fall of the steel balls in the two mineral oils and the emulsions of these oils are shown in Tables II, III and IV. In general, an increase in the water concentration of an emulsion resulted in a decrease in the falling rate.

The data obtained for the three McMurray oils and the emulsions of these oils are shown in Tables V, VI and VII. A complete run at five different temperatures and five water concentrations was done on the McMurray oil diluted with 16.9% kerosine. Since the viscosity of the McMurray oils increases rapidly with a decrease in kerosine dilution, it was possible to get the rates of fall at only the higher temperatures. Runs were made with two emulsions of approximately 20% and 30% water with the 6.29% dilution at the three highest temperatures. Data for the undiluted McMurray oil were obtained at the two highest temperatures and for the emulsions of approximately 20% and 30% water.

The rate of fall of the steel balls increased with temperature for all McMurray oils, and the increase in water concentration of the emulsions decreased the fall rate in all cases.

A comparison of the effect of change of ball diameter on velocity at 160°F for the five dry oils examined is shown in Fig. 3. The graph indicates close resemblance between the pure mineral oils and the three McMurray oils.

The effect of ball diameter on the fall rate in emulsions of 30% water at 160°F for the five oils is shown in Fig. 4. Again



TABLE II

Rates of fall of steel balls of various diameters  
at various temperatures in emulsions of water in  
Grade 100 Aviation lubricating oil,

| Temperature, °F.    | Diameter of ball, in.  |       |       |      |      |      |
|---------------------|------------------------|-------|-------|------|------|------|
|                     | 1/16                   | 3/32  | 1/8   | 3/16 | 1/4  | 3/8  |
|                     | Rate of fall, in./sec. |       |       |      |      |      |
| Water conc., 0%:    |                        |       |       |      |      |      |
| 70                  | 0.545                  | 1.17  | 2.02  | 4.14 | 6.75 | 12.2 |
| 100                 | 1.62                   | 3.37  | 5.23  | 10.1 | 14.6 | 22.6 |
| 130                 | 3.48                   | 6.43  | 9.46  | 16.1 | -    | -    |
| 160                 | 5.90                   | 9.94  | 14.0  | 21.4 | -    | -    |
| 180                 | 7.34                   | 11.8  | 16.2  | 24.3 | -    | -    |
| Water conc., 2.93%: |                        |       |       |      |      |      |
| 70                  | 0.494                  | 1.09  | 1.85  | 3.96 | 6.28 | 11.9 |
| 100                 | 1.45                   | 3.11  | 5.09  | 9.57 | 14.2 | 22.0 |
| 130                 | 3.34                   | 6.62  | 9.35  | 15.4 | -    | -    |
| 160                 | 5.65                   | 9.62  | 13.7  | 20.8 | -    | -    |
| Water conc., 5.23%: |                        |       |       |      |      |      |
| 70                  | 0.471                  | 1.03  | 1.78  | 3.74 | 6.09 | 11.2 |
| 100                 | 1.40                   | 3.02  | 4.82  | 9.21 | 13.3 | 21.3 |
| 130                 | 3.13                   | 6.02  | 9.46  | 15.4 | -    | -    |
| 160                 | 5.32                   | 9.13  | 13.0  | 20.3 | -    | -    |
| Water conc., 10.2%: |                        |       |       |      |      |      |
| 70                  | 0.415                  | 0.901 | 1.53  | 3.26 | 5.32 | 10.2 |
| 100                 | 1.23                   | 2.62  | 4.33  | 8.21 | 11.9 | 20.1 |
| 130                 | 2.78                   | 5.44  | 8.41  | 14.1 | -    | -    |
| 160                 | 4.83                   | 8.60  | 12.4  | 19.4 | -    | -    |
| Water conc., 21.1%: |                        |       |       |      |      |      |
| 70                  | 0.291                  | 0.626 | 1.10  | 2.32 | 3.89 | 7.53 |
| 100                 | 0.865                  | 1.92  | 3.29  | 6.63 | 10.4 | 17.1 |
| 130                 | 2.06                   | 4.23  | 6.51  | 11.6 | -    | -    |
| 160                 | 3.79                   | 7.11  | 10.2  | 16.9 | -    | -    |
| Water conc., 27.1%: |                        |       |       |      |      |      |
| 70                  | 0.216                  | 0.484 | 0.853 | 1.82 | 3.02 | 6.01 |
| 100                 | 0.649                  | 1.48  | 2.54  | 5.34 | 8.49 | 14.8 |
| 130                 | 1.55                   | 3.36  | 5.59  | 10.1 | -    | -    |
| 160                 | 3.06                   | 5.90  | 8.84  | 15.7 | -    | -    |



TABLE II I

Rates of fall of steel balls of various diameters at various temperatures in emulsions of water in Grade 140 Aviation lubricating oil.

| Temperature, °F.    | Diameter of ball, in.  |       |       |       |      |      |
|---------------------|------------------------|-------|-------|-------|------|------|
|                     | 1/16                   | 3/32  | 1/8   | 3/16  | 1/4  | 3/8  |
|                     | Rate of fall, in./sec. |       |       |       |      |      |
| Water conc., 0%:    |                        |       |       |       |      |      |
| 70                  | 0.275                  | 0.600 | 1.03  | 2.17  | 3.73 | 7.07 |
| 100                 | 0.908                  | 1.95  | 3.31  | 6.57  | 9.96 | 16.5 |
| 130                 | 2.25                   | 4.41  | 6.88  | 12.1  | 16.8 | 26.2 |
| 160                 | 4.30                   | 7.63  | 10.9  | 17.4  | 23.1 | 33.6 |
| 180                 | 5.61                   | 9.23  | 13.5  | 21.1  | -    | -    |
| Water conc., 2.50%: |                        |       |       |       |      |      |
| 70                  | 0.259                  | 0.583 | 1.03  | 2.23  | 3.80 | 7.73 |
| 100                 | 0.863                  | 1.85  | 3.21  | 6.31  | 9.74 | 16.8 |
| 130                 | 2.13                   | 4.30  | 6.63  | 11.8  | 16.8 | 25.7 |
| 160                 | 3.98                   | 7.42  | 10.7  | 16.9  | -    | -    |
| 180                 | 5.55                   | 9.27  | 13.4  | 20.3  | -    | -    |
| Water conc., 4.60%: |                        |       |       |       |      |      |
| 70                  | 0.242                  | 0.527 | 0.911 | 1.99  | 3.31 | 6.42 |
| 100                 | 0.789                  | 1.76  | 2.99  | 6.01  | 9.41 | 16.6 |
| 130                 | 2.02                   | 4.03  | 6.34  | 11.3  | 16.2 | 25.0 |
| 160                 | 3.82                   | 7.04  | 11.2  | 17.1  | -    | -    |
| 180                 | 5.23                   | 8.95  | 12.4  | 19.4  | -    | -    |
| Water conc., 9.22%: |                        |       |       |       |      |      |
| 70                  | 0.219                  | 0.480 | 0.820 | 1.77  | 2.99 | 5.76 |
| 100                 | 0.719                  | 1.55  | 2.65  | 5.43  | 8.35 | 14.6 |
| 130                 | 1.73                   | 3.75  | 5.76  | 10.4  | 14.6 | 22.4 |
| 160                 | 3.47                   | 6.63  | 9.83  | 16.8  | -    | -    |
| 180                 | 4.92                   | 8.49  | 12.4  | 19.0  | -    | -    |
| Water conc., 25.1%: |                        |       |       |       |      |      |
| 70                  | 0.112                  | 0.259 | 0.451 | 0.968 | 1.72 | 3.40 |
| 100                 | 0.404                  | 0.915 | 1.60  | 3.36  | 5.37 | 10.1 |
| 130                 | 1.08                   | 2.38  | 3.97  | 7.59  | 11.6 | 18.6 |
| 160                 | 2.31                   | 4.60  | 7.17  | 12.5  | -    | -    |
| 180                 | 3.33                   | 6.34  | 9.37  | 15.2  | -    | -    |
| Water conc., 38.7%: |                        |       |       |       |      |      |
| 70                  | 0.0964                 | 0.206 | 0.364 | 0.812 | 1.37 | 2.75 |
| 100                 | 0.324                  | 0.717 | 1.25  | 2.64  | 4.43 | 8.16 |
| 130                 | 0.806                  | 1.79  | 3.02  | 6.16  | 9.13 | 16.0 |
| 160                 | 1.79                   | 3.71  | 5.84  | 10.8  | -    | -    |
| 180                 | 2.66                   | 5.15  | 7.86  | 13.5  | -    | -    |



TABLE IV

Rates of fall of steel balls of various diameters  
at various temperatures in emulsions of water in  
Grade 140 Aviation lubricating oil.

| Temperature, °F.              | Diameter of ball, in.  |       |      |      |
|-------------------------------|------------------------|-------|------|------|
|                               | 3/32                   | 1/8   | 3/16 | 1/4  |
|                               | Rate of fall, in./sec. |       |      |      |
| Water conc., 0%:              |                        |       |      |      |
| 70                            | 0.606                  | 1.06  | 2.17 | 3.73 |
| 100                           | 1.99                   | 3.30  | 6.56 | 9.94 |
| 130                           | 4.62                   | 7.16  | 12.3 | 17.1 |
| Water conc., 0%, oil. worked: |                        |       |      |      |
| 70                            | 0.615                  | 1.07  | 2.31 | 3.79 |
| 100                           | 1.96                   | 3.28  | 6.56 | 10.0 |
| 130                           | 4.59                   | 7.10  | 12.4 | 17.4 |
| Water conc., 0.71%:           |                        |       |      |      |
| 70                            | 0.604                  | 1.05  | 2.22 | 3.78 |
| 100                           | 1.93                   | 3.23  | 6.45 | 9.72 |
| 130                           | 4.58                   | 7.14  | 12.3 | 17.8 |
| Water conc., 1.33%:           |                        |       |      |      |
| 70                            | 0.598                  | 1.02  | 2.21 | 3.74 |
| 100                           | 1.88                   | 3.19  | 6.25 | 9.74 |
| 130                           | 4.55                   | 6.97  | 11.8 | 17.8 |
| Water conc., 1.90%:           |                        |       |      |      |
| 70                            | 0.583                  | 1.02  | 2.14 | 3.62 |
| 100                           | 1.90                   | 3.29  | 6.39 | 9.79 |
| 130                           | 4.38                   | 7.35  | 11.8 | 17.1 |
| Water conc., 2.43%:           |                        |       |      |      |
| 70                            | 0.583                  | 1.02  | 2.14 | 3.48 |
| 100                           | 1.90                   | 3.18  | 6.36 | 9.72 |
| 130                           | 4.45                   | 6.88  | 11.8 | 16.8 |
| Water conc., 2.82%:           |                        |       |      |      |
| 70                            | 0.570                  | 0.994 | 2.14 | 3.53 |
| 100                           | 1.93                   | 3.14  | 6.36 | 9.64 |
| 130                           | 4.36                   | 6.94  | 11.8 | 16.9 |
| Water conc., 3.30%:           |                        |       |      |      |
| 70                            | 0.562                  | 0.992 | 2.13 | 3.53 |
| 100                           | 1.88                   | 3.07  | 6.14 | 9.27 |
| 130                           | 4.30                   | 6.45  | 11.4 | 16.0 |
| Water conc., 4.90%:           |                        |       |      |      |
| 70                            | 0.530                  | 0.920 | 1.95 | 3.25 |
| 100                           | 1.73                   | 3.01  | 5.91 | 9.41 |
| 130                           | 4.08                   | 6.29  | 10.9 | 15.9 |



TABLE V

Rates of fall of steel balls of various diameters  
at various temperatures in emulsions of water in  
McMurray oil diluted with 16.9% kerosine.

| Temperature °F.     | Diameter of ball, in.  |       |       |       |       |      |
|---------------------|------------------------|-------|-------|-------|-------|------|
|                     | 1/16                   | 3/32  | 1/8   | 3/16  | 1/4   | 3/8  |
|                     | Rate of fall, in./sec. |       |       |       |       |      |
| Water conc., 0%:    |                        |       |       |       |       |      |
| 70                  | 0.135                  | 0.298 | 0.513 | 1.09  | 1.81  | 3.47 |
| 100                 | 0.571                  | 1.23  | 2.09  | 4.26  | 6.73  | 11.8 |
| 130                 | 1.63                   | 3.37  | 5.46  | 9.47  | 13.6  | -    |
| 160                 | 3.47                   | 6.42  | 9.51  | 14.4  | 20.3  | -    |
| 180                 | 4.86                   | 8.33  | 11.6  | 18.6  | 24.3  | -    |
| Water conc., 2.80%: |                        |       |       |       |       |      |
| 70                  | 0.127                  | 0.284 | 0.486 | 1.03  | 1.73  | 3.35 |
| 100                 | 0.536                  | 1.15  | 2.02  | 4.09  | 6.41  | 11.3 |
| 130                 | 1.56                   | 3.23  | 5.31  | 9.11  | 13.4  | -    |
| 160                 | 3.38                   | 6.12  | 9.00  | 14.8  | 19.9  | -    |
| 180                 | 4.53                   | 8.25  | 11.5  | 18.2  | 23.8  | -    |
| Water conc., 4.98%: |                        |       |       |       |       |      |
| 70                  | 0.123                  | 0.267 | 0.472 | 0.999 | 1.67  | 3.27 |
| 100                 | 0.513                  | 1.11  | 1.93  | 3.86  | 6.28  | -    |
| 130                 | 1.44                   | 3.03  | 4.94  | 8.95  | 12.9  | -    |
| 160                 | 3.26                   | 5.87  | 8.75  | 14.4  | 19.4  | -    |
| 180                 | 4.50                   | 8.01  | 11.1  | 17.6  | 23.4  | -    |
| Water conc., 9.53%: |                        |       |       |       |       |      |
| 70                  | 0.109                  | 0.233 | 0.397 | 0.851 | 1.41  | 2.73 |
| 100                 | 0.445                  | 0.966 | 1.66  | 3.43  | 5.64  | -    |
| 130                 | 1.29                   | 2.68  | 4.47  | 8.30  | 11.8  | -    |
| 160                 | 2.67                   | 5.21  | 8.03  | 13.3  | 18.2  | -    |
| 180                 | 3.89                   | 7.04  | 10.1  | 16.1  | 21.3  | -    |
| Water conc., 18.5%: |                        |       |       |       |       |      |
| 70                  | 0.0781                 | 0.155 | 0.296 | 0.632 | 1.03  | 2.02 |
| 100                 | 0.319                  | 0.684 | 1.17  | 2.42  | 3.98  | -    |
| 130                 | 0.948                  | 2.02  | 3.31  | 6.48  | 9.43  | -    |
| 160                 | 2.06                   | 3.94  | 6.32  | 11.2  | 15.3  | -    |
| 180                 | 3.05                   | 5.65  | 8.43  | 13.9  | 18.9  | -    |
| Water conc., 25.5%: |                        |       |       |       |       |      |
| 70                  | 0.0541                 | 0.128 | 0.210 | 0.460 | 0.756 | 1.44 |
| 100                 | 0.243                  | 0.530 | 0.883 | 1.83  | 3.04  | -    |
| 130                 | 0.692                  | 1.51  | 2.55  | 5.34  | 7.84  | -    |
| 160                 | 1.58                   | 3.33  | 5.31  | 9.35  | 13.3  | -    |
| 180                 | 2.35                   | 4.77  | 7.29  | 12.5  | 17.3  | -    |



TABLE VI

Rates of fall of steel balls of various diameters  
at various temperatures in emulsions of water in  
McMurray oil diluted with 6.28% kerosine.

| Temperature, °F.    | Diameter of ball, in.  |       |      |      |
|---------------------|------------------------|-------|------|------|
|                     | 3/32                   | 1/8   | 3/16 | 1/4  |
|                     | Rate of fall, in./sec. |       |      |      |
| Water conc., 0%:    |                        |       |      |      |
| 130                 | 1.41                   | 2.39  | 4.86 | 7.46 |
| 160                 | 3.59                   | 5.82  | 9.62 | 13.9 |
| 180                 | 5.48                   | 8.09  | 13.1 | 18.2 |
| Water conc., 18.3%: |                        |       |      |      |
| 130                 | 0.716                  | 1.34  | 2.78 | 4.60 |
| 160                 | 1.95                   | 3.24  | 6.42 | 9.23 |
| 180                 | 2.93                   | 4.87  | 9.04 | 13.1 |
| Water conc., 30.6%: |                        |       |      |      |
| 130                 | 0.433                  | 0.738 | 1.48 | 2.22 |
| 160                 | 0.960                  | 1.75  | 3.86 | 5.57 |
| 180                 | 1.56                   | 2.73  | 6.06 | 9.51 |

TABLE VII

Rates of fall of steel balls of various sizes  
at various temperatures in emulsions of water  
in undiluted McMurray oil.

| Temperature, °F.    | Diameter of ball, in.  |       |      |      |
|---------------------|------------------------|-------|------|------|
|                     | 3/32                   | 1/8   | 3/16 | 1/4  |
|                     | Rate of fall, in./sec. |       |      |      |
| Water conc., 0%:    |                        |       |      |      |
| 160                 | 1.69                   | 2.86  | 5.49 | 8.35 |
| 180                 | 3.14                   | 5.06  | 8.93 | 12.5 |
| Water conc., 18.5%: |                        |       |      |      |
| 160                 | 0.818                  | 1.51  | 3.17 | 4.92 |
| 180                 | 1.54                   | 2.53  | 5.58 | 8.33 |
| Water conc., 31.4%: |                        |       |      |      |
| 160                 | 0.436                  | 0.831 | 1.59 | 2.45 |
| 180                 | 0.584                  | 1.20  | 2.91 | 4.75 |



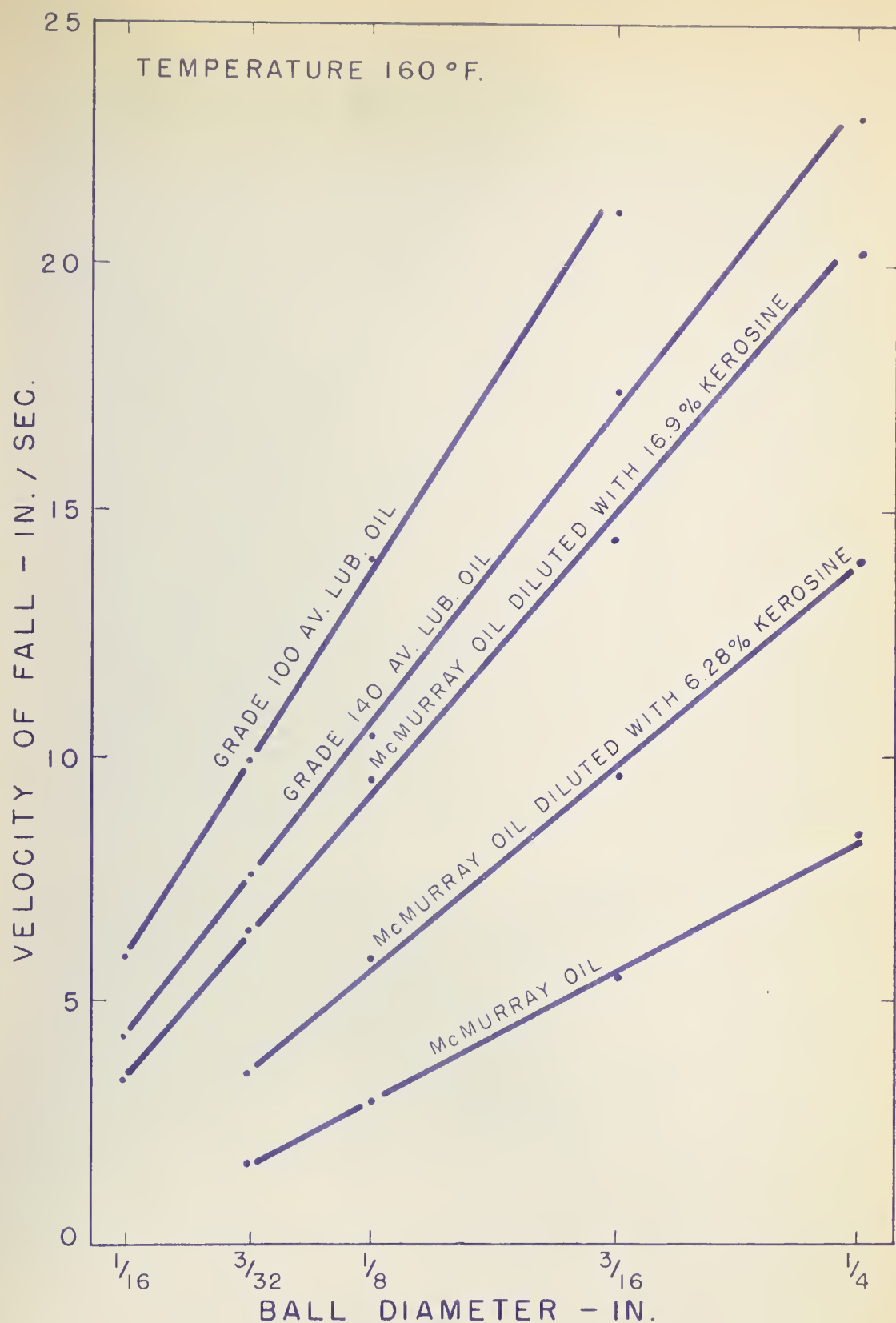


Fig. 3. Relation between observed velocity of fall and ball diameter for two dry refined oils and three dry crude oils at 160°F.



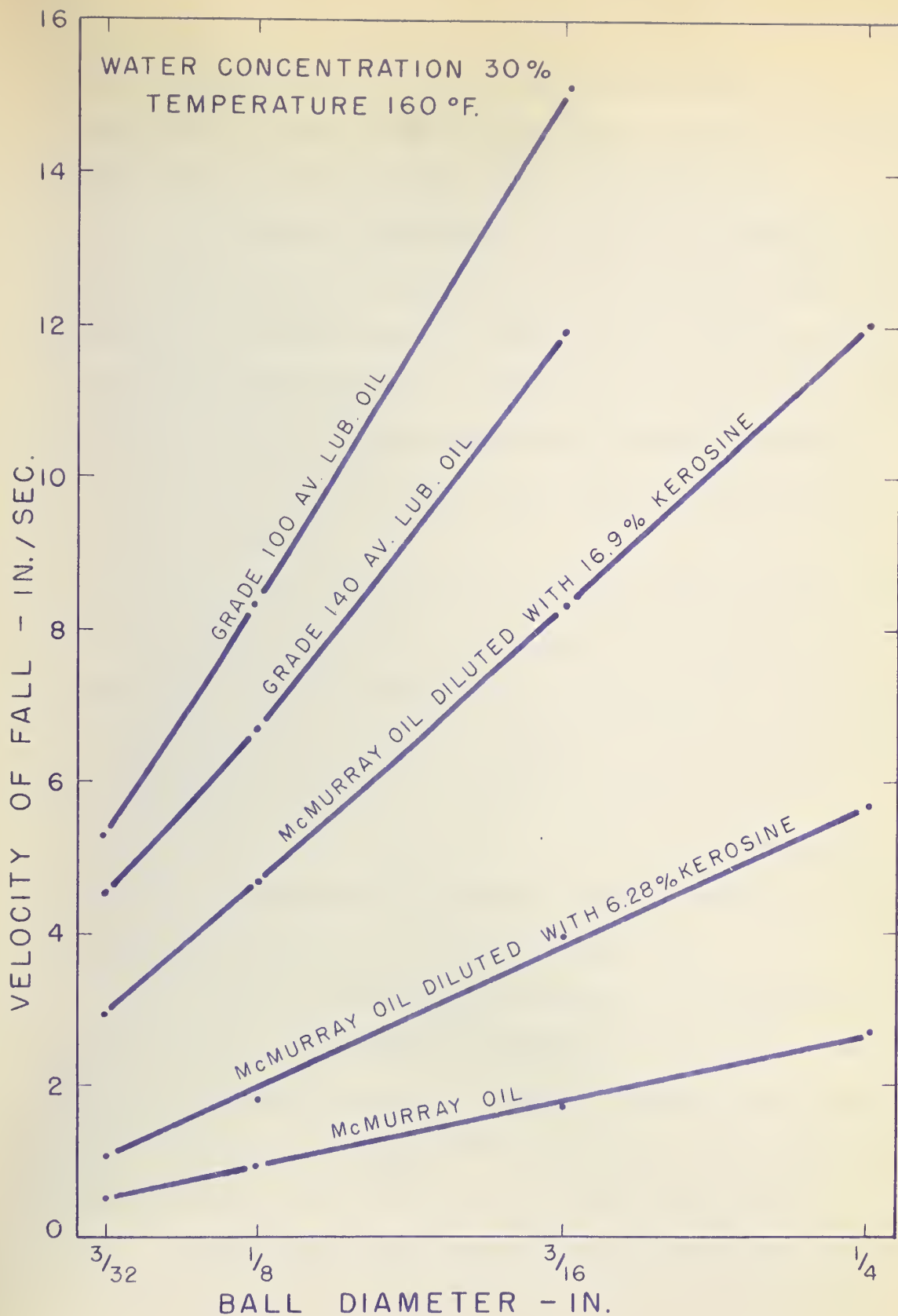


Fig. 4. Relation between observed velocity of fall and ball diameter in emulsions of 30% water in two refined oils and three crude oils at 160°F.



very close similarity is shown for the five emulsions. It is interesting to note in both Fig. 3 and 4 that the lines converge at approximately zero ball diameter and zero velocity.

An anomalous behaviour was observed for the emulsion of 2.50% water in Grade 140 aviation oil as shown in Table III. The dropping rate increased with the addition of this amount of water. Two possible explanations were suggested for this phenomenon. The viscosity of the oil may have decreased by two possible means;

1. A working effect, known to exist in some types of greases
2. The dilution effect of a small amount of water.

Another run on Grade 140 aviation oil was made. The rates of fall were determined first on the unworked oil. The oil was cycled with the emulsifier running for a period equivalent to the time taken to prepare the emulsion of 2.50% water, but no water was added. The rates of fall were then determined on the worked oil. No appreciable difference could be observed in the rates of fall between the worked and unworked oils.

Water was added in small increments of approximately 0.75% in order to try to detect a maximum in the fall rate. The results of this run are shown in Table IV. A plot of these rates of fall against water concentration again showed a very slight increase between one and three per cent water concentration.

These results appear to show that the anomaly is caused by a dilution effect rather than by any structural change in the



oil itself due to working. However the effect was small, and it disappeared at higher water concentrations.

Before examining the emulsion systems in detail it was necessary to determine whether or not they were Newtonian in character. A Newtonian fluid is one in which the rate of shear is proportional to the shearing stress. A method of determining whether a liquid is Newtonian or non-Newtonian is to determine its viscosity at different rates of shear. The viscosity of a 5% emulsion of Grade 140 Aviation oil was determined by the Modified Ostwald method using tubes of different capillary diameters. The results in Table VIII indicate that the emulsions can be considered Newtonian in character.

Table VIII

Comparison of viscosity of emulsion using various diameter capillaries (Modified Ostwald Method).

| Tube | Efflux time, sec. | Viscosity, centistokes. |
|------|-------------------|-------------------------|
| 1    | 58.9              | 455                     |
| 2    | 373.8             | 456.0                   |
| 3    | 1709              | 457.5                   |

The rates of fall were determined for various emulsions of Grade 140 aviation oil at 100°F. and are shown in Table IX. The Stokes's velocity corrected for wall effect is also shown. Eliminating all results in which the Reynolds number exceeded one, the rate of fall was substituted into the Stokes's equation and the viscosities of



TABLE IX

Comparison of velocities\*corrected for wall effect  
with determined velocities at 100°F. for emulsions  
of Grade 140 Aviation lubricating oil.

|                    |                        |       |       |        |
|--------------------|------------------------|-------|-------|--------|
| Water conc., %     | 2.50                   | 4.60  | 9.22  | 25.1   |
| Viscosity, poises. | 4.141                  | 4.419 | 4.802 | 8.17** |
| Method.            | Rate of fall, in./sec. |       |       |        |

Ball diameter, 1/16 in.:

|                      |       |       |       |       |
|----------------------|-------|-------|-------|-------|
| Stokes, uncor.       | 0.897 | 0.840 | 0.772 | 0.455 |
| Stokes, Bacon cor.   | 0.848 | 0.793 | 0.730 | 0.430 |
| Stokes, Francis cor. | 0.848 | 0.794 | 0.730 | 0.430 |
| Determined.          | 0.863 | 0.789 | 0.719 | 0.404 |

Ball diameter, 3/32 in.:

|                      |      |      |      |       |
|----------------------|------|------|------|-------|
| Stokes, uncor.       | 2.02 | 1.89 | 1.74 | 1.02  |
| Stokes, Bacon cor.   | 1.86 | 1.74 | 1.60 | 0.940 |
| Stokes, Francis cor. | 1.86 | 1.74 | 1.60 | 0.940 |
| Determined.          | 1.85 | 1.76 | 1.55 | 0.915 |

Ball diameter, 1/8 in.:

|                      |      |      |      |      |
|----------------------|------|------|------|------|
| Stokes, uncor.       | 3.59 | 3.36 | 3.09 | 1.82 |
| Stokes, Bacon cor.   | 3.19 | 2.99 | 2.75 | 1.62 |
| Stokes, Francis cor. | 3.20 | 3.00 | 2.76 | 1.62 |
| Determined.          | 3.21 | 2.99 | 2.65 | 1.60 |

Ball diameter, 3/16 in.:

|                      |      |      |      |      |
|----------------------|------|------|------|------|
| Stokes, uncor.       | 8.07 | 7.55 | 6.95 | 4.09 |
| Stokes, Bacon cor.   | 6.74 | 6.31 | 5.81 | 3.42 |
| Stokes, Francis cor. | 6.77 | 6.33 | 5.83 | 3.43 |
| Determined.          | 6.31 | 6.01 | 5.43 | 3.36 |

Ball diameter, 1/4 in.:

|                      |      |      |      |      |
|----------------------|------|------|------|------|
| Stokes, uncor.       | 14.3 | 13.4 | 12.3 | 7.28 |
| Stokes, Bacon cor.   | 11.2 | 10.5 | 9.66 | 5.69 |
| Stokes, Francis cor. | 11.3 | 10.5 | 9.72 | 5.73 |
| Determined.          | 9.74 | 9.41 | 8.35 | 5.37 |

\* Velocities calculated by Stokes's equation.

\*\* Value obtained by graphical interpolation.



the emulsions were determined. The viscosities of the emulsions were determined also by using a Modified Ostwald tube. A comparison of these results is shown in Table X.

Table X  
Comparison of Emulsion Viscosities  
Determined by Falling Ball and Modified Ostwald Methods.

| Water<br>concentration, % | Viscosity, poises. |                   |
|---------------------------|--------------------|-------------------|
|                           | Falling ball.      | Modified Ostwald. |
| 2.50                      | 4.11               | 4.14              |
| 4.60                      | 4.41               | 4.42              |
| 9.22                      | 4.93               | 4.80              |
| 25.1                      | 8.42               | 8.17              |

The results indicate that the viscosity of an emulsion determined by means of a Modified Ostwald Viscometer may be used in the Stokes's equation for predicting the terminal velocity of a particle falling through the emulsion.

A comparison between the falling rate as predicted by the Stokes's equation and the determined velocities for the two dry mineral oils is shown in Tables XI and XII. Corresponding data for the dry McMurray oil diluted with 16.9% kerosine is shown in Table XIII. The predicted values were corrected for wall effect by the formulas of Bacon and Francis. The viscosity values used in the Stokes's equation were determined with a Modified Ostwald Viscometer.

Good agreement was obtained for the smaller balls falling in high viscosity oils, where the Reynolds number was one or less.



TABLE XI

Comparison of velocities corrected for wall effect  
with determined velocities for Grade 100 Aviation  
lubricating oil at various temperatures.

| Temperature, °F.   | 70                     | 100   | 130    | 160    | 180    |
|--------------------|------------------------|-------|--------|--------|--------|
| Viscosity, poises. | 6.460                  | 2.153 | 0.8789 | 0.4310 | 0.2869 |
| Method.            | Rate of fall, in./sec. |       |        |        |        |

Ball diameter, 1/16 in.:

|                      |       |      |      |      |      |
|----------------------|-------|------|------|------|------|
| Stokes, uncor.       | 0.575 | 1.73 | 4.22 | 8.64 | 12.9 |
| Stokes, Bacon cor.   | 0.543 | 1.63 | 3.99 | 8.17 | 12.2 |
| Stokes, Francis cor. | 0.544 | 1.64 | 3.99 | 8.17 | 12.3 |
| Determined.          | 0.545 | 1.63 | 3.48 | 5.90 | 7.34 |

Ball diameter, 3/32 in.:

|                      |      |      |      |      |      |
|----------------------|------|------|------|------|------|
| Stokes, uncor.       | 1.29 | 3.88 | 9.53 | 19.5 | 29.2 |
| Stokes, Bacon cor.   | 1.18 | 3.56 | 8.75 | 17.9 | 26.9 |
| Stokes, Francis cor. | 1.18 | 3.56 | 8.75 | 17.9 | 26.9 |
| Determined.          | 1.17 | 3.37 | 6.43 | 9.94 | 11.9 |

Ball diameter, 1/8 in.:

|                      |      |      |      |      |      |
|----------------------|------|------|------|------|------|
| Stokes, uncor.       | 2.31 | 6.48 | 15.9 | 34.7 | 52.2 |
| Stokes, Bacon cor.   | 2.05 | 5.77 | 14.1 | 30.8 | 46.3 |
| Stokes, Francis cor. | 2.06 | 5.78 | 14.2 | 30.9 | 46.4 |
| Determined.          | 2.02 | 5.23 | 9.46 | 14.0 | 16.2 |

Ball diameter, 3/16 in.:

|                      |      |      |      |      |       |
|----------------------|------|------|------|------|-------|
| Stokes, uncor.       | 5.18 | 15.5 | 38.1 | 77.7 | 116.9 |
| Stokes, Bacon cor.   | 4.31 | 12.9 | 31.8 | 64.9 | 97.6  |
| Stokes, Francis cor. | 4.34 | 13.0 | 31.9 | 65.2 | 98.0  |
| Determined.          | 4.14 | 10.1 | 16.1 | 21.4 | 24.3  |

Ball diameter, 1/4 in.:

|                      |      |      |   |   |   |
|----------------------|------|------|---|---|---|
| Stokes, uncor.       | 9.18 | 27.6 | - | - | - |
| Stokes, Bacon cor.   | 7.17 | 21.6 | - | - | - |
| Stokes, Francis cor. | 7.22 | 21.7 | - | - | - |
| Determined.          | 6.28 | 14.2 | - | - | - |

| TABLE I |      |     |     |            | SUMMARY OF RESULTS |         |
|---------|------|-----|-----|------------|--------------------|---------|
| Case    | Year | Age | Sex | Occupation | Findings           | Remarks |
| 1       | 1901 | 25  | M   | Farmer     | ...                | ...     |
| 2       | 1902 | 30  | F   | Housewife  | ...                | ...     |
| 3       | 1903 | 40  | M   | Teacher    | ...                | ...     |
| 4       | 1904 | 50  | F   | Shopkeeper | ...                | ...     |
| 5       | 1905 | 60  | M   | Retired    | ...                | ...     |
| 6       | 1906 | 70  | F   | Widow      | ...                | ...     |
| 7       | 1907 | 80  | M   | Old man    | ...                | ...     |
| 8       | 1908 | 90  | F   | Old woman  | ...                | ...     |
| 9       | 1909 | 100 | M   | Very old   | ...                | ...     |
| 10      | 1910 | 110 | F   | Very old   | ...                | ...     |
| 11      | 1911 | 120 | M   | Very old   | ...                | ...     |
| 12      | 1912 | 130 | F   | Very old   | ...                | ...     |
| 13      | 1913 | 140 | M   | Very old   | ...                | ...     |
| 14      | 1914 | 150 | F   | Very old   | ...                | ...     |
| 15      | 1915 | 160 | M   | Very old   | ...                | ...     |
| 16      | 1916 | 170 | F   | Very old   | ...                | ...     |
| 17      | 1917 | 180 | M   | Very old   | ...                | ...     |
| 18      | 1918 | 190 | F   | Very old   | ...                | ...     |
| 19      | 1919 | 200 | M   | Very old   | ...                | ...     |
| 20      | 1920 | 210 | F   | Very old   | ...                | ...     |

TABLE XII

Comparison of velocities corrected for wall effect  
with determined velocities for Grade 140 Aviation  
lubricating oil at various temperatures.

| Temperature, °F.   | 70                     | 100   | 130   | 160    | 180    |
|--------------------|------------------------|-------|-------|--------|--------|
| Viscosity, poises. | 12.56                  | 3.884 | 1.502 | 0.6885 | 0.4434 |
| Method.            | Rate of fall, in./sec. |       |       |        |        |

Ball diameter, 1/16 in.:

|                      |       |       |      |      |      |
|----------------------|-------|-------|------|------|------|
| Stokes, uncor.       | 0.295 | 0.956 | 2.48 | 5.40 | 8.40 |
| Stokes, Bacon cor.   | 0.279 | 0.904 | 2.34 | 5.11 | 7.93 |
| Stokes, Francis cor. | 0.279 | 0.904 | 2.34 | 5.11 | 7.93 |
| Determined.          | 0.275 | 0.908 | 2.25 | 4.30 | 5.61 |

Ball diameter, 3/32 in.:

|                      |       |      |      |      |      |
|----------------------|-------|------|------|------|------|
| Stokes, uncor.       | 0.663 | 2.16 | 5.57 | 12.1 | 18.9 |
| Stokes, Bacon cor.   | 0.608 | 1.98 | 5.12 | 11.1 | 17.4 |
| Stokes, Francis cor. | 0.608 | 1.98 | 5.12 | 11.1 | 17.4 |
| Determined.          | 0.600 | 1.95 | 4.41 | 7.63 | 9.23 |

Ball diameter, 1/8 in.:

|                      |      |      |      |      |      |
|----------------------|------|------|------|------|------|
| Stokes, uncor.       | 1.18 | 3.84 | 9.93 | 21.7 | 33.7 |
| Stokes, Bacon cor.   | 1.05 | 3.42 | 8.84 | 19.3 | 30.0 |
| Stokes, Francis cor. | 1.05 | 3.42 | 8.86 | 19.4 | 30.1 |
| Determined.          | 1.03 | 3.31 | 6.88 | 10.9 | 13.5 |

Ball diameter, 3/16 in.:

|                      |      |      |      |      |      |
|----------------------|------|------|------|------|------|
| Stokes, uncor.       | 2.66 | 8.61 | 18.4 | 48.7 | 75.6 |
| Stokes, Bacon cor.   | 2.22 | 7.19 | 15.3 | 40.6 | 63.2 |
| Stokes, Francis cor. | 2.23 | 7.22 | 15.3 | 40.8 | 63.4 |
| Determined.          | 2.17 | 6.57 | 12.1 | 17.4 | 21.1 |

Ball diameter, 1/4 in.:

|                      |      |      |      |      |   |
|----------------------|------|------|------|------|---|
| Stokes, uncor.       | 4.75 | 15.3 | 39.7 | 86.8 | - |
| Stokes, Bacon cor.   | 3.71 | 12.0 | 31.0 | 67.8 | - |
| Stokes, Francis cor. | 3.73 | 12.1 | 31.3 | 68.3 | - |
| Determined.          | 3.73 | 9.96 | 16.8 | 23.1 | - |



TABLE XIII

Comparison of velocities corrected for wall  
effect with determined velocities at various  
temperatures for McMurray oil diluted with  
16.9% kerosine.

| Temperature, °F.   | 70                     | 100   | 130   |
|--------------------|------------------------|-------|-------|
| Viscosity, poises. | 24.17                  | 6.571 | 2.181 |
| Method.            | Rate of fall, in./sec. |       |       |

Ball diameter, 1/16 in.:

|                     |       |       |      |
|---------------------|-------|-------|------|
| Stokes, uncor.      | 0.151 | 0.557 | 1.68 |
| Stokes, Bacon cor.  | 0.142 | 0.526 | 1.59 |
| Stokes, Francis co. | 0.143 | 0.526 | 1.59 |
| Determined.         | 0.135 | 0.571 | 1.63 |

Ball diameter, 3/32 in.:

|                      |       |      |      |
|----------------------|-------|------|------|
| Stokes, uncor.       | 0.340 | 1.25 | 3.78 |
| Stokes, Bacon cor.   | 0.312 | 1.15 | 3.47 |
| Stokes, Francis cor. | 0.312 | 1.15 | 3.47 |
| Determined.          | 0.298 | 1.23 | 3.37 |

Ball diameter, 1/8 in.:

|                      |       |      |      |
|----------------------|-------|------|------|
| Stokes, uncor.       | 0.605 | 2.23 | 6.72 |
| Stokes, Bacon cor.   | 0.538 | 1.98 | 5.98 |
| Stokes, Francis cor. | 0.538 | 1.99 | 6.00 |
| Determined.          | 0.513 | 2.09 | 5.46 |

Ball diameter, 3/16 in.:

|                      |      |      |      |
|----------------------|------|------|------|
| Stokes, uncor.       | 1.36 | 5.02 | 15.1 |
| Stokes, Bacon cor.   | 1.14 | 4.18 | 12.6 |
| Stokes, Francis cor. | 1.14 | 4.20 | 12.7 |
| Determined.          | 1.09 | 4.26 | 9.47 |

Ball diameter, 1/4 in.:

|                      |      |      |      |
|----------------------|------|------|------|
| Stokes, uncor.       | 2.42 | 8.91 | 26.9 |
| Stokes, Bacon cor.   | 1.89 | 6.96 | 21.0 |
| Stokes, Francis cor. | 1.91 | 7.01 | 21.2 |
| Determined.          | 1.81 | 6.73 | 13.6 |



The divergence from the predicted value increased as the Reynolds number increased. The predicted value was about three times the determined value at a Reynolds number of 90, the highest Reynolds number reached in the present investigation. The large divergence between the predicted and determined values can be considered due to leaving the region of laminar flow and approaching the turbulent region, where Stokes's law no longer applies.

Rayleigh's (18) criterion that the Reynolds number must be less than one was applied to all the results obtained. Fig. 5 shows the ratio of the predicted velocity to the determined velocity plotted against the Reynolds number for the dry McMurray oils. There is a very well-defined break in the curve when the Reynolds number exceeds one. The same result was observed for the refined oils.

Comparing the dry oils with the corresponding emulsions, it was found that the emulsions were characterized by a lower rate of fall resulting from a higher viscosity. The change in density was small. Consequently if a ball falling in a particular dry oil was characterized by a certain Reynolds number, the same ball in the corresponding emulsion had a lower Reynolds number.

The particle size of the disperse phase was determined by a photomicrograph as shown in Plate II to be in the range of one to twenty microns. Bancelin (3) working with suspensions of particles which ranged from 0.6 to 8.0 microns in diameter showed that the viscosity was independent of particle size. The size of the water droplets in emulsions in the present study was approximately in the



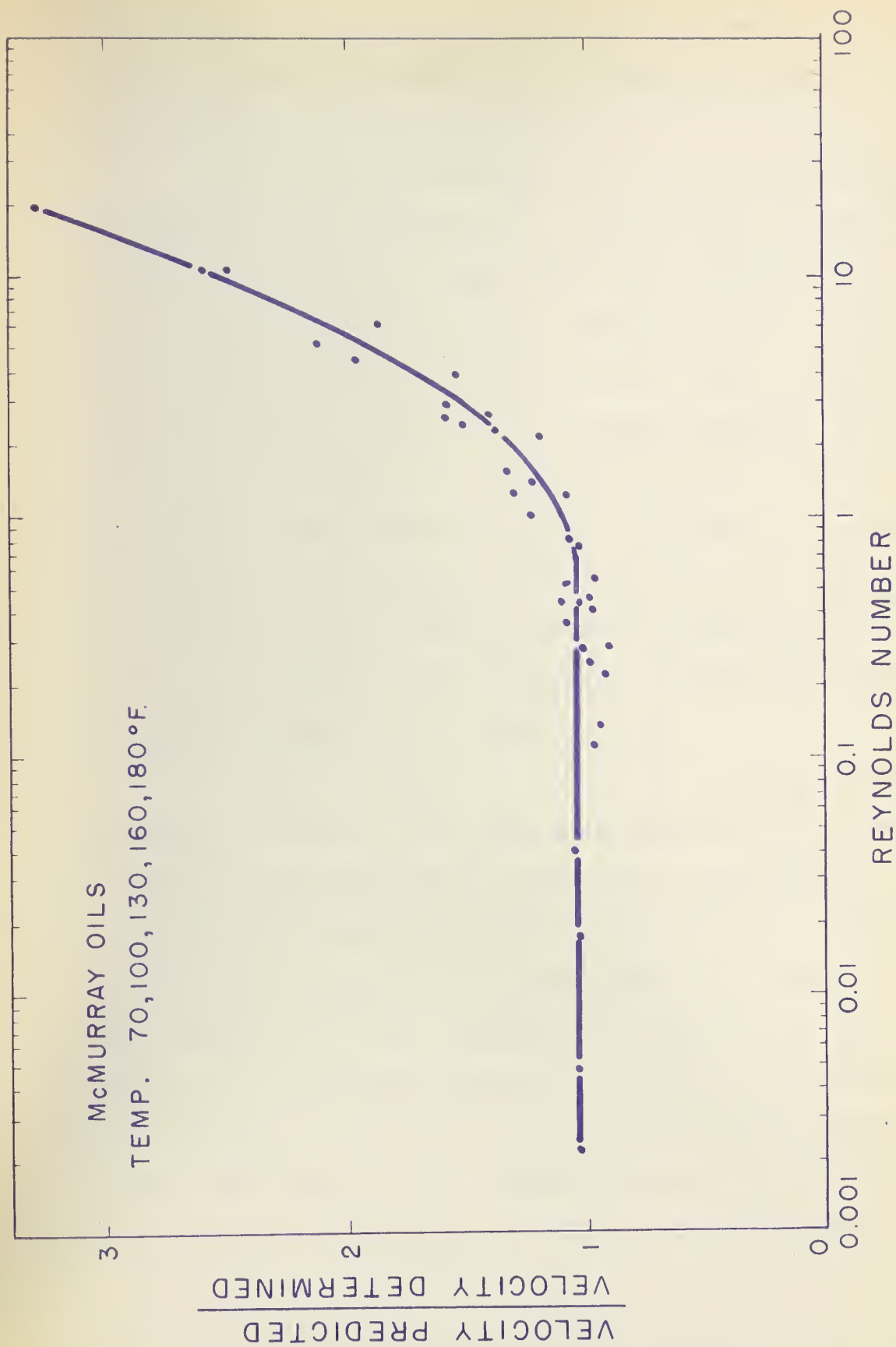


Fig. 5. Curve illustrating lack of agreement between predicted and observed velocities at Reynolds number greater than one for three dry McMurray oils at five temperatures.



same order as those studied by Bancelin. The viscosities of the emulsions were therefore considered to be independent of particle size, as required by the Einstein equation.

The ratio of the viscosity of the emulsion to the viscosity of the dry oil was calculated for all systems where the Reynolds number was less than one. These results were independent of wall effect, since the correction factors cancelled out in every case. Good agreement was obtained between different diameter balls in any particular emulsion. This ratio was therefore independent of ball diameter and temperature. Two graphs were made with this ratio plotted against water concentration, one for the two refined oils and the other for the three McMurray oils. The curves were very similar, with the curve for the refined oils falling slightly below the curve for the McMurray at the higher water concentrations. The curve for the three McMurray oils is shown in Fig. 6.

The general pattern of this graph is in good agreement with those obtained for the viscosity concentration curves of various sols by previous investigators. Sulphur sols investigated by Oden (16) and various protein sols studied by Chick (6) both showed an increase in viscosity as the concentration of the disperse phase was increased. All curves appeared to be linear up to a concentration of 10% of the disperse phase, after which point the viscosity rose rapidly with an increase in the concentration of the disperse phase. This indicates that the Einstein equation holds for low concentrations of the disperse phase in water-in-oil emulsions but



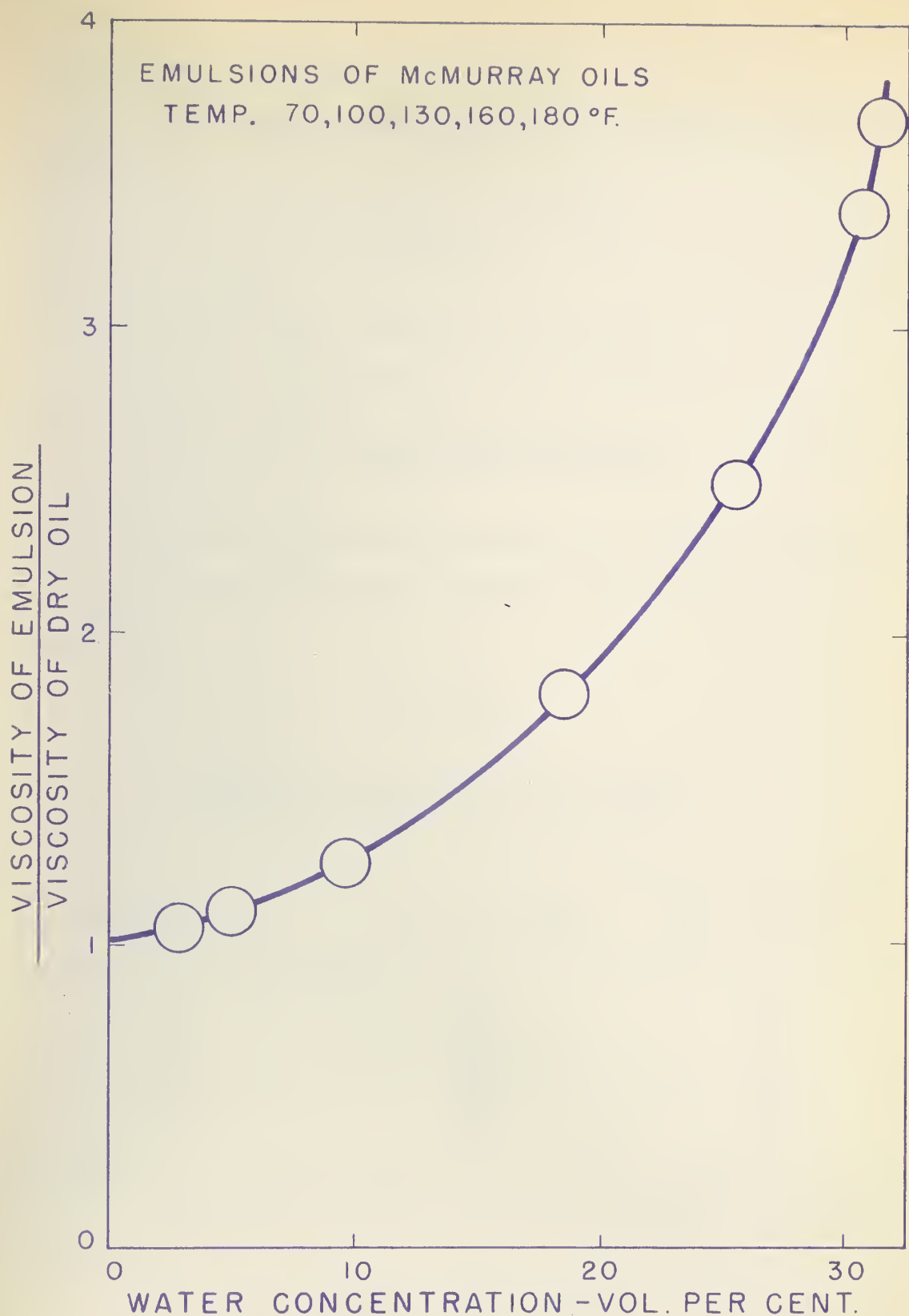


Fig. 6. Curve illustrating change of viscosity with water concentration for emulsions of three McMurray oils at five temperatures.



fails beyond the 10% point.

The equation for the curve for the refined oil was found to be:

$$n = n_o(1 + c + 14c^2 + 8c^3) \quad (1)$$

where

$n_o$  = viscosity of the dry oil,

$n$  = viscosity of the emulsion,

$c = \frac{\text{volume of water}}{\text{total volume of emulsion}}$

The determined values and those predicted by the above equation are compared in Table XIV and good agreement over the range studied is apparent.

Table XIV

Comparison of determined values with those predicted by equation (1) for various water concentrations with refined oil.

| Water<br>concentration, % | $\frac{n}{n_o}$ , determined | $\frac{n}{n_o}$ , calculated |
|---------------------------|------------------------------|------------------------------|
| 5                         | 1.13                         | 1.09                         |
| 10                        | 1.31                         | 1.25                         |
| 15                        | 1.50                         | 1.50                         |
| 20                        | 1.80                         | 1.82                         |
| 25                        | 2.24                         | 2.24                         |
| 30                        | 2.80                         | 2.78                         |

The equation for the curve for the McMurray oil was found to be:

$$n = n_o(1 + c + 14c^2 + 26c^3) \quad (2)$$



The determined values and those predicted by the above equation are compared in Table XV. Good agreement is apparent over the range studied.

Table XV

Comparison of determined values with those predicted by equation (2) for various water concentrations in McMurray oil.

| Water<br>concentration, % | $\frac{n}{n_o}$ , determined | $\frac{n}{n_o}$ , calculated |
|---------------------------|------------------------------|------------------------------|
| 5                         | 1.10                         | 1.09                         |
| 10                        | 1.28                         | 1.27                         |
| 15                        | 1.58                         | 1.56                         |
| 20                        | 1.95                         | 1.97                         |
| 25                        | 2.45                         | 2.52                         |
| 30                        | 3.25                         | 3.25                         |

For determining the rate of fall for any particle in an emulsion of McMurray oil the viscosity of the emulsion can be determined from the equation once the water concentration and the viscosity of the dry oil are known. The density and radius of the particle can be determined by inspection. By applying this data to the Stokes's equation, the settling rate for any particle may be predicted, providing the flow system is in the laminar region. Since McMurray oils are viscous and the particle size of sand granules is small, it is safe to assume that all settling will occur in laminar flow.



SUMMARY

The conclusions resulting from this investigation may be summarized as follows.

1. Emulsions of water-in-oil are Newtonian in character, providing the temperature of the oil is in the range where the oil itself is Newtonian.
2. The viscosity of a water-in-oil emulsion can be used in the Stokes's equation for predicting the rate of fall.
3. The viscosity of an emulsion of McMurray oil can be calculated from the viscosity of the dry oil and the water concentration by the equation:

$$n = n_o(1 + c + 14c^2 + 26c^3).$$



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